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Adverbs and Adjectives: An Abstraction for Software Defined Radio

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Abstract

Many wireless network and transport protocols take advantage of the interaction between the physical and link layers to achieve reasonable performance, reliability, and energy efficiency. Such "cross-layer" dependences are typically explicitly enumerated in order to cause predetermined behavior in the physical and link layers. The need for cross layer interaction will only increase as advanced physical and link interfaces are realized in software radio systems (SDRs). In order to meet the demands of large systems of heterogeneous software radios we will have to develop application and system programming interfaces that are highly flexible and portable. This paper demonstrates how a set of modifiers for the "verbs" and "nouns" in communication protocols can achieve the performance, flexibility, and portability improvements required. Adverbs in our abstraction, such as send locally *and* send reliably, *are used rather than explicit directives. Modifiers like these provide freedom for each layer in the protocol stack to choose from a proven palette of cross-layer techniques. This work presents a subset of potential modifiers and their application. The promise of the abstraction is illustrated through simulation of the* send locally *adverb.*

1 Introduction

Software Defined Radios (SDRs) promise to redefine wireless communications in numerous and profound ways. The ability to dynamically redefine the lower layers of a radio device offers tremendous opportunities to improve communication capabilities and efficiencies. This is in stark contrast to the static nature of traditional radio devices, which tend toward fixed operational modes and potentially inefficient use of the available RF spectrum. Beyond these technical (and regulatory) limitations, the static nature of the protocol stacks associated with these devices further limits their potential efficiency. This type of inefficiency is often due to the fact that higher layers make incorrect assumptions about lower layers and channel conditions. Such inefficiencies are further exposed when the protocols are evaluated against new metrics such as energy efficiency, overhead or impact on the noise floor. As a result, cross-layer approaches to overcome these deficiencies have become a common theme in the literature.

Such cross layer interactions occur at different layers of the network. For example, TCP may depend on the link layer for information about the cause of packet loss or expiration of timers. In the absence of such knowledge, TCP may relate the cause to network congestion. In reality it might be that transient noise introduced extra errors. Similarly, one may depend on the routing, link and physical layer to provide the QoS. The routing layer may try to use multiple routes while the link layer may assist by choosing less congested links. Similarly the routing protocol also depends on the lower layers. Originally, many protocols were designed with little consideration of the properties of lower layer layers of the protocol stack; for example, application protocols largely viewed wireless networks as being similar to wired networks. However, lower layers (link and physical layer) play a significant role in achieving good performance in wireless networks. For example, choosing a higher capacity link at the physical layer or avoiding nodes with high link-layer contention can improve the throughput dramatically. Other desirable network performance metrics may also be met through cross layer interactions. For example, energy consumption, though a physical layer property, may depend on the needs of the higher layers. A routing protocol may vary transmission power depending on its need to reach just one or many nodes.

As a result, one may ask the question *how should such cross layer interaction be expressed?* In this paper, we propose a framework for cross layer interactions. In this, we can abstract the higher layer interaction from the lower layers using *adverbs*. In the traditional linguistic context, adverbs

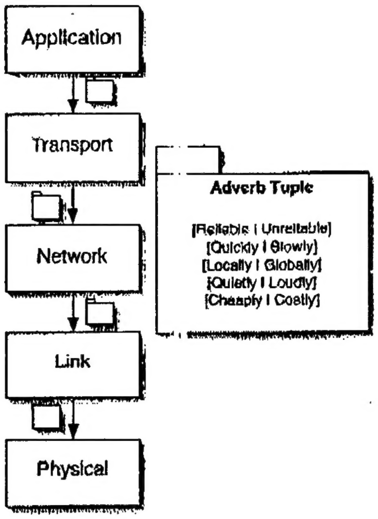


Figure 1: The adverb tuple is passed down the protocol stack. Each layer can select a mechanism to optimize performance according to the specified attributes.

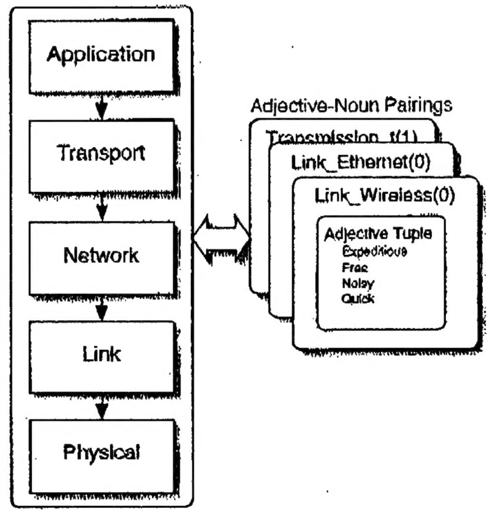


Figure 2: Each layer in the TCP/IP stack is able to access, modify, and/or act upon adjective-noun pairings optimizing performance or changing behavior according to the specified attributes.

are used to modify verbs, adjectives or other adverbs. In our model, we apply the adverb analogy to modifying verbs associated with the communications. For example, one might want the data to be send "quickly", "reliably" or "locally". Similarly, the properties of the layers can be abstracted using an *adjective*. Again, in the traditional context adjectives are used to describe nouns. In our model, an adjective is used to describe a communication attribute. For example, a network link can be "capacious" the medium can be described as "noisy".

The organization of the paper is as follows. We first describe our framework of adverbs and adjectives in Section 2. Then in Section 3 we show that using our more abstract framework allows us to improve the performance of a routing protocol using two distinct mechanisms available in the lower layers. One mechanism, transmission power control, is managed by the physical layer. The other mechanism, transmission rate control, is managed by the link layer. Either mechanism can be used to control the range of message transmissions. We also show that both mechanisms have similar effect on goodput in an 802.11b network and argue that they can be used interchangeably or in combination, resulting in improved routing algorithms that are more flexible than those that explicitly control a single mechanism. We then briefly review the considerable body of work that has explored cross-layer protocol design in Section 4. We conclude the paper by discussing our results and future work.

2 Conceptual Model

It is our belief that by modifying commands with information that is illustrative of the applications requirements we can improve the overall performance of the protocol stack. Standard communication protocols, routing algorithms and applications send commands to affect lower layers. Our framework treats commands as verbs that can be modified through the use of adverbs. A tuple of adverbs is attached to the command.

As shown in Figure 1, an application generates an adverb tuple consisting of its communication requirements and passes this information down the stack. The layers read and autonomously act on the adverb tuple by selecting mechanisms that optimize performance according to tuple attributes. More specifically, the routing layer may instruct the link layer to send *quickly*. This can be interpreted at the link layer as choosing a link with more available bandwidth. Notice that the mechanism for how the link layer reacts to the modified command is not specified as part of the adverb tuple. The adverb abstraction allows the lower layer to choose any suitable mechanism to honor higher layer requests. In an advanced system that incorporates a software-defined radio (SDR), the adverb tuple could cause the link and physical layer to dynamically reconfigure the interface. The SDR would then be able to more efficiently use the spectrum available in the ISM band, possibly forming a single high-speed channel. This newly formed channel would greatly surpass the bandwidth offered by standard 802.11a/b/g solutions.

The methodology used in grafting a set of adverbs onto commands can also be applied to dynamically characterize

properties of the communication environment. The adverb to command framework was extended to make use of adjectives to modify layer properties, expressed as nouns, in order to realize dynamism and performance gains. In Figure 2, the layers of the TCP/IP stack are able to access and modify the adjectives that pertain to a paired noun. Each of the layers can then take action to maximize performance based on how a property is modified by its adjectives. One should note that the depicted noun and adjective tuple are one of many possibilities. In this instance the noun refers to the wireless link w0.

We contend that an adjective tuple can have a positive effect when paired with nouns that describe layer properties. For instance, a noun, *link status*, could be paired with adjectives like *busy*. In the 802.11 MAC protocol if a node wishes to transmit and another node is transmitting, the station attempting to communicate must defer its transmission. If we were to use the busy adjective with respect to link status, other layers could act upon this information. A system incorporating SDR could use this information to switch the transmitter to another channel and bypass the busy link without waiting. Thus, by using adjectives we are able encapsulate communication and environmental properties without using explicit parameters or values.

It is important to note that adjective and adverb tuples can be interpreted and acted upon differently through and across the layers in the protocol stack. The adverb *locally* at the application layer could mean finding a printer physically near you. At the routing layer, it may mean finding a node fewer than two hops away.

The model we present here serves as basis from which a more complete framework can be constructed and is not intended to be all encompassing. Rather, it was constructed to illustrate the viability of such an approach to improving performance, reliability, and energy consumption.

2.1 Adverbs

The following subsections serve to illustrate how adverb-command pairings may interact in our notional framework. Again, the adverbs discussed are not an exhaustive collection; rather, they serve to demonstrate the viability of our model.

2.1.1 Quickly vs. Slowly

The IEEE 802.11a/b/g standards are multi-rate in that they provide physical-layer mechanisms to transmit at higher rate than the base rate, if channel conditions permit. For example, the 802.11b standard offers different transmission rates such as 1, 2, 5.5 and 11Mbs. As a result, different link layer protocols were designed to exploit the availability of higher transmission rates. Auto Rate Fallback (ARF) was the first commercial implementation using this multi-rate capability at the MAC layer. With ARF, senders use the history of previous transmission error rates to adaptively select future transmission rates. Receiver Based Auto Rate (RBAR) is an enhanced protocol designed to exploit the multi-rate capabilities of the MAC layer [1]. RBAR lets the receiver control the sender's transmission rate through RTS/CTS negotiation.

RBAR and ARF are protocols that negotiate the transmission rates at the link layer. It is important to realize that the routing layer remains ignorant of such link layer properties. Alternatively, by using our framework, one could attach the adverb, *quickly*, to the routing layer tuple allowing the link layer to route data to the destination node using the faster link. This can be achieved if the routing layer can instruct the link layer to send the data rapidly. The link layer will choose to send the data at higher transmission rate if the channel conditions permit. Or the link layer could optionally send the data over a less congested link, honoring the higher layer request with an entirely different mechanism[2, 3].

The application layer can also have different QoS requirements; naturally, one of these is sending data quickly. The quickly adverb may be honored at the routing layer by choosing the routes that guarantee the latency specified[4, 5]. Subsequently, the link layer could negotiate between different nodes choosing the quicker link. Alternatively, different classes of traffic could be introduced by changing the link layer back off; thus offering another means to send data quickly.

The adverb *slowly* refers to the case where there is not a requirement to send data quickly. There are many classes of traffic that do not require low latency and high bandwidth. One could imagine a SDR that would dynamically select a slower, noisy link for a FTP session, or forwarding of email traffic, based on an adverb tuple that contains slowly.

2.1.2 Locally vs. Globally

It is widely believed that the key factor in building scalable network is the locality of the network traffic[6]. In other words, each node talks directly only to the nodes within a fixed radius, independent of network size. Using a large transmission range causes more interference with neighboring network traffic and reduces performance. Clearly, there is strong motivation for routing *locally*.

An obvious course of action to take in the presence of an adverb tuple which contains the *locally* adverb is for the physical layer to send the packet at a lower transmission power. This results in a shorter transmission range and reduces the amount of RF interference generated by the transmission of that packet.

Alternatively the link layer could change the packet transmission rate. Different transmission rates use different modulation techniques. Higher transmission rates use encodings that are faster to transmit, but are also more suscep-

Transmission rate	Open range
1 Mb/s	550m
2 Mb/s	400m
5.5 Mb/s	270m
11 Mb/s	160m

Table 1: Open range for a Orinoco Gold card

tible to error and hence require a better signal to noise ratio for successful reception. This is often expressed in terms of distance in open space, *i.e.*, an unobstructed, open field with minimal outside RF interference. Table 1 shows the specified ranges of communication at different transmission rates for an Orinoco Gold 802.11b card. Thus when encountering the adverb, *locally*, the link layer can reduce the successful packet reception range by selecting a higher transmission rate. While this does not reduce the area over which the packet produces RF interference (as is the case when reducing transmission power), it does reduce the *time* required to transmit the packet. We will explore the details of how altering these lower layer network properties, *i.e.*, transmission power and symbol encoding interacts with higher layers in the network stack in section 3.

Conversely the routing layer may want to route packets *globally*. In a less congested medium, one may want to send the packets globally if one is unable to find a route locally. If different traffic sources in the network are using separate physical channels, it may be more efficient to send data globally as it will reduce the number of hops without causing interference with neighboring traffic. Through the high-level abstraction provided by adverbs the lower protocol layers may achieve the globally goal using one or both of the mechanisms described.

At the application layer the adverb locally could have different implication. A user may wish to find a printer locally. The underlying routing protocol may honor it by supplying information about the printers in the same subnet. Alternatively, some geographical routing may help in choosing a physically close printer.

The power of our abstraction is even more clearly realized when using SDR; many of the mechanisms available with a fully software defined radio would not have been considered by most protocol designers. If a radio has the ability to widely shift the frequency used, the *locally* adverb can be implemented by frequency shifting. As shown in Figure 3, low frequencies, such as in the short-wave band, have far reach but low bandwidth, whereas higher frequencies tend to have shorter range and increased bandwidth. Specific frequencies (such as that around 60Ghz) have a pronounced attenuation due to absorption in oxygen. A SDR system, in order to fulfill the *locally* adverb, could select the 60Ghz band to limit its transmission range. The framework frees an algorithm designer from encapsulating knowledge of oxygen absorption in their algorithms. The mechanism for meeting

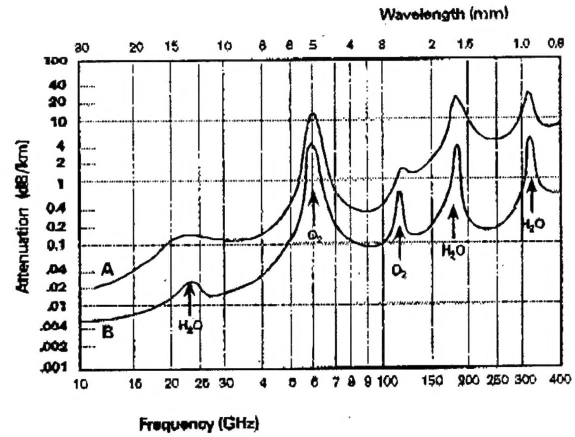


Figure 3: Signal attenuation across the millimeter-wave RF spectrum

the intent of the adverb tuple is left in the hands of the expert. In this case, the designer of the SDR antenna hardware and software.

2.1.3 Cheaply vs. Costly

Reducing energy consumption by wireless communication devices is one of the most important concerns in designing an 802.11 solution. Although transmit power is a physical layer property, higher layers can also play an important role in determining the energy consumed by a node. For example, a proactive routing protocol will spend more energy than a reactive protocol, simply by virtue of sending more packets. By using the *cheaply* or potentially defining a *conservatively* adverb, the link and physical layers may chose to transmit and/or route in a manner that optimizes energy consumption. Additionally, the application layer may assist by using better compression on the data. Cross layer contributions can also be built upon at the transport layer. This layer, by being more cautious about initiating congestion control, can contribute to the overall goal of transmitting cheaply. Alternatively, the routing layer may choose to route data through energy-rich nodes [7]. It may also choose to send fewer routing packets, or the layer may choose to send larger sized packets rather than sending multiple small packets. Additionally, the link layer may determine an optimal combination of transmission rate and transmission power control to minimize the energy consumption [8]. Again, the abstraction provides a large amount of flexibility to enhance performance both within and across layers.

One could imagine a scenario where all links are congested, noisy or down. The application could then incorporate the costly adverb in the tuple. As a result the lower layers could dynamically select a link that requires the user to pay a fee for use. Also, when you have a powered base station, energy constraints may not be a concern and one

may consider expensive transferring of data or possibly be more charitable about routing data for others.

2.1.4 Reliably vs. Unreliably

The dynamic nature of mobile networking is attributed to variable link characteristics, node movements, changing network topology, and variable application demands. As a result, it can be quite hard to guarantee reliable transmission of packets. Although reliable protocols such as TCP aim to provide end-to-end guarantees, the lower layers can also play a powerful role in improving network reliability and performance [9, 10, 11]. It is a logical assertion that the higher layer may wish to instruct the lower layer to help in sending data *reliably*. Again, the reliable attribute of the adverb tuple in our framework can have intra and cross layer benefits.

At the transport layer, this may be realized by choosing a reliable protocol such as TCP or SCTP. The routing layer may choose to use multiple routes to send data so as to ensure reliability [12, 13]. Further, the link layer may choose to send the data at a lower transmission rate while making maximum use of error correction. Additionally, a choice can be made to send data over different physical channels to minimize contention and reduce packet corruption and delay. An SDR has the added flexibility to redundantly send the data over multiple spectrum ranges.

2.1.5 Quietly vs. Loudly

Due to the broadcast nature of the wireless media, when two hosts are communicating, all other hosts within the range of the two hosts must defer their transmissions in order to avoid a collision. Hidden terminals also complicate and contribute to the congestion problem. Performance degrades further when interfering with a bottleneck node. One can see the potential advantage in sending data quietly. Through the use of our framework one could gain a tremendous advantage by facilitating intelligent use of transmission space and spatial reuse. An SDR equipped with a narrow beam steerable antenna would have a dramatic impact on the ability of nodes to transmit concurrently. The flexibility of the framework is again realized across layers.

At the routing layer, this may be done by choosing maximally disjoint routes [14]. Through routing one may proactively try to avoid formation of bottleneck nodes. Additionally, the link layer may choose to reduce the transmission range, thereby reducing the number of nodes impacted by its transmission. Also, the link layer may choose to send the data in different physical channel, reducing the effect on other traffic [15, 16, 17]. At the physical layer, an SDR may also help by switching to a block of quiet spectrum to send the data.

2.2 Adjectives

The following discussion illustrates how adjective-noun pairings may interact in our notional framework. Like the previous subsections, the adjectives discussed here are not an exhaustive collection; rather, they serve to demonstrate the viability of our model.

2.2.1 Link - Busy

The 802.11 MAC protocol employs carrier sense multiple access with collision avoidance (CSMA/CA). In this protocol, the node first senses the medium. If the medium is busy, i.e., some other node is transmitting, the station defers its transmission to a later time. This can often lead to packet delay and expiration of network timers. If the adjective *busy* were paired with the link, the transport layer via TCP, could interpret *busy* as congestion and take necessary corrective measures. In addition, the application layer could change its QoS requirements based on this information. A streaming video application could dynamically switch to buffering more data in light of the busy media.

2.2.2 Link - Noisy

Transient noise and inhospitable physical conditions may also cause packet loss, high errors and expiration of network timers. In this instance the medium is noisy rather than busy. Wireless media is more susceptible to transient noise. Without the availability of information afforded by the adjective framework, higher layer protocols such as TCP may incorrectly assume the cause of the packet loss was congestion. TCP congestion control over a noisy link may make the situation worse. An SDR may use spread spectrum transmission techniques to minimize the impact of noise. Some advanced antenna technologies are also able to emit energy patterns to cancel out noise.

2.2.3 Other Adjectives

One can imagine a myriad of additional adjectives that could serve to enhance our framework. In the adhoc networking domain one could imagine the noun *topology* being modified by adjectives like *mobile* or *stable*. An SDR acting upon this information could reconfigure to use favorable routing algorithms, more efficient symbol encoding, or exploit spatial reuse through antenna directionality. We believe that our framework when paired with an SDR has the potential to offer huge improvements in performance, energy use, and overall responsiveness to the users desires. The following section serves to demonstrate the potential of the framework through simulation.

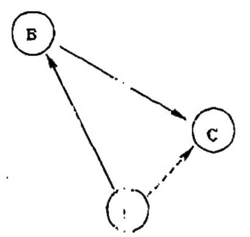


Figure 4: Formation of needle:ly long routes in a pathological case

3 In depth: Rout("locally"

Network wide broadcasting .; a fundamental operation in wireless *ad hoc* networks. It: goal is to transmit a message from a source node to many :r all nodes in the network. It is generally employed by th: source node to search for a route to the destination node. Unfortunately, broadcasting increases congestion in the r:twork while also causing interference with neighboring r:twork traffic.

Due to increased interfere:ce, the performance of *ad hoc* networks can be significantl: degraded. Li [6] argued that the key factor in building sc:lable *ad hoc* networks is the locality of network traffic. I: other words, each node talks only to the nodes within a fi·ed radius, independent of the network size. In such a case the per-node capacity of the network remains constant. Ti.is, there is a strong motivation for nodes to communicate m:stly with local nodes and thus most routing will probably b: local as well.

Another motivation for : node to route "locally" is to prevent formation of needles:ly long routes. Figure 4 illustrates this situation. In this :igure, node A is trying to find route to node C and broadca:ts a "route request" message. That message reaches nodes : and C, but node B replies before node C and the route $A \rightarrow B \rightarrow C$ is formed at node A. Meanwhile, node C's rep:y is lost due to congestion or is prevented from replying a: the medium is busy with B's reply. Such a situation can o:cur during a broadcast storm when a node is trying to find : route. Alternatively, if node A were able to limit the propag::ion range of a route request, it would only communicate wit:. node C, resulting in the direct route of $A \rightarrow C$.

As mentioned, broadcast :nd unicast packets are usually sent at different transmissio: rates. The broadcast packets are usually sent at the base frequency (1Mb/s or 2Mb/s) and thus reach a greater nu:ber of nodes. Unfortunately, this can result in situations :vhere a node can hear broadcasts from another node, b:t not be able to reply using a higher data rate. For ex:mple, node B may receive a route request from node A, :ut may not be able to directly reply at 11Mb/s. This pro:lem can be mitigated by the use of link layer rate negoti:tion protocols such as RBAR (Receiver-Based AutoRate) [1]. The RBAR protocol establishes the optimal transmiss:on rate to send the packet via RTS/CTS exchange. Although it prevents the situation described above, this negotiation takes time.

These link layer problems are exacerbated by the flooding nature of most route request mechanisms. If node B did not know of a route to node C, it may re-broadcast the route request on behalf of node A. Many routing algorithms, including AODV (Ad Hoc On Demand Distance Vector Protocol) use such an "expanding ring" to try to locate routes. Hence, the notion of routing "locally" is appealing. The routing layer may achieve the notion of routing "locally" with some assistance from the link layer, as explained in Section 2.1.2. On the request of the routing layer, the physical layer may reduce the transmit power of the broadcast request packets or the link layer can send it at higher transmission rate. This technique reduces its transmission range but not the interference range. Alternatively, the system may use a combination of these two mechanisms as dictated by the channel conditions.

If the *ad hoc* routing protocols are oblivious to lower layer characteristics such as transmission range, it is hard or impossible for it to do "local" routing. This problem is further exaggerated by the fact that most routing protocols were designed with certain assumptions about the lower layers, such as a single-rate link layer or a single transmission power for all packets. Our abstraction frees the application or system level programmer from relying on specific lower layer capabilities in order to realize performance gains.

3.1 One adverb, two mechanisms, similar outcome

We conducted an experiment to evaluate the effect of changing transmission rate and transmission power individually. Two mechanisms are used to in this experiment to gauge the impact of the "local" adverb on routing performance. While using transmission rate control, each node sends the request packet at a fixed transmission rate (either 11, 5.5 2 or 1 Mb/s). Each transmission rate has varying transmission range, as shown in Table 1, resulting in varying effective throughputs at different transmission rates. In another set of simulations, we varied the transmission power. We selected four transmission power levels that would result in effective communication ranges approximating those of the transmission rates. For example, the 5.5mb/s transmission rate has an effective range of 270m, we selected a transmit power level that also had an effective range of 270m. The rate or power of both broadcast and unicast packets are controlled, but only the range of the broadcast packets is controlled by the routing layer. The unicast packets use the RBAR [1] adaptive rate control mechanism. By using this technique the differences in performance arise from route selection, not just from effective data transmission rates.

Transmit power control is more flexible than changing transmission rate since the power level can usually be

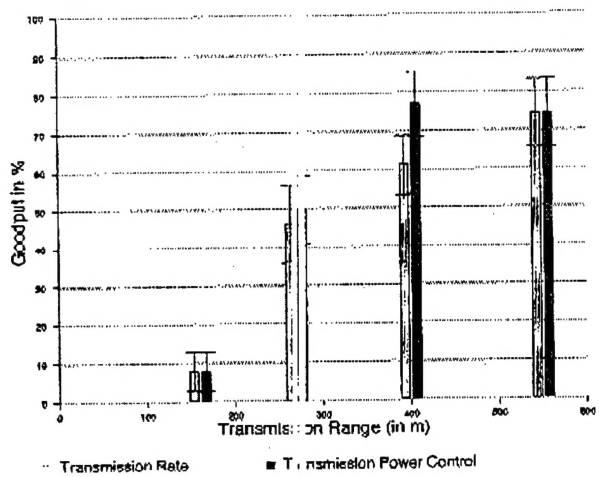


Figure 5: The effect of using transmission power control and transmission rate on goodput. The x-axis represents the transmission range, which is kept the same using power control and transmission rate in both cases.

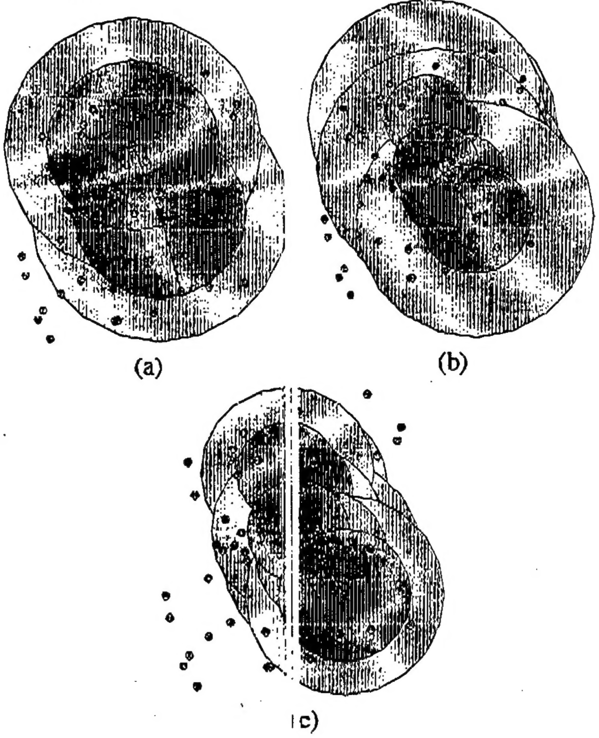


Figure 6: Visual representation of noise imparted by a single end-to-end transmission. The darker shade represents the transmission range while the lighter shade represents carrier sensing range in (a) Default AODV with 1Mb transmission rate for broadcast packets, (b) Stateful algorithm using transmission rate control and (c) Stateful algorithm using transmission power control

more finely controlled, but not all wireless interfaces support transmission power adjustments. Similarly, not all interfaces support multiple transmission rates. It should be noted that the ability to change transmit rate as well as transmission power of each individual packet is supported by many modern chipsets, e.g., the Atheros[18] 802.11a/b/g chips and the Intersil Prisim family of 802.11b chips.

Our results for a static wireless scenario are summarized in Figure 5. The horizontal axis in the graph corresponds to the transmission range achieved by increasing rate from 11Mbs to 1Mbs or by suitably changing transmission power. The error bars record the 95% confidence interval across different nodes. The two mechanisms (power *vs.* rate) result in statistically indistinguishable goodputs at each power level. The goodput achieved decreases for smaller transmission range because reducing the range of the broadcast request packets partitions the network. Intuitively, we would expect higher goodput with a higher transmission rate. However, in this simulation, we used a fairly low traffic injection rate(4 packets/s, 64 bytes/packet) thus did not gain from using the higher capacity links.

Reducing the transmission power reduces the carrier sensing range as well as reducing the transmission range. However, using transmission rate control only decreases the transmission range while the carrier sense range does not change. For the lowest transmission range, the difference in performance with both rate and power control is negligible since the dominant factor affecting the performance is network partitioning. Similarly, the default highest transmission range has similar behavior since both transmission range and carrier sense range are same.

The difference between the transmission range and carrier sense range is illustrated in Figure 6, which shows a single end-to-end (*i.e.*, multi-hop) transmission's effect on the network noise floor. The darker shade in the figure represents the transmission range while the lighter shade represents the carrier sense range. Figure 6(a) shows standard behavior corresponding to broadcast packets being sent at the longest transmission range (*i.e.*, 1Mbs). Figure 6(b) illustrates the effect of transmission rate control. By reducing the transmission range we also reduce the active neighbor count. However, because power is unaffected, it still has the same carrier sensing range as that of Figure 6(a) thus it stops an equal number of nodes from transmitting. In Figure 6(c), using power control not only reduces the transmission range but also changes the carrier sense range, allowing more nodes to transmit.

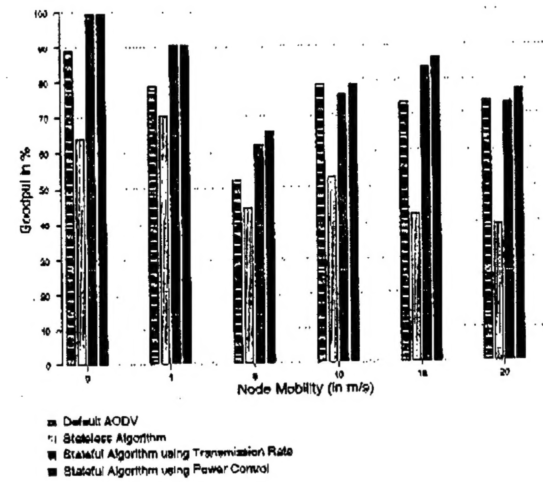
The impact of each mechanism, power *vs.* rate, depends on a number of factors including node density, node mobility, environmental factors and so on. This simple example illustrates that two differing mechanisms can have similar impact on performance. To fully compare the impact of both mechanisms, we turn to an in-depth simulation study of an *ad hoc* algorithm modified to use "local" routing.

3.2 Modifying AODV to use "local" routing

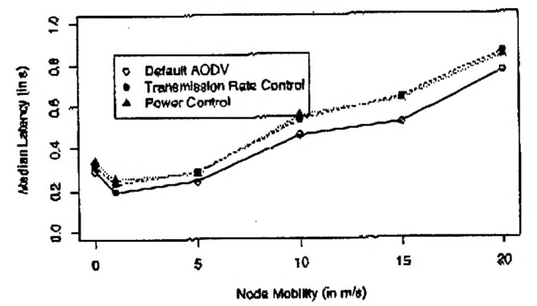
Several researchers have investigated using transmission power control to improve throughput in *ad hoc* networks [19, 20, 21, 22]. The general goal of this research is to limit interference between multiple communicating nodes. This is important both for route requests and standard unicast messages as mentioned above. By limiting route requests, the number of route replies is also limited, thus reducing the large amount of routing overhead seen in high mobility environments where routes are frequently broken. We are able to provide overall greater capacity by using the "locally" adverb to limit transmission power.

To realize the "locally" adverb we added cross-layer modifications to the AODV protocol. The routing layer adjusts the transmission rate or transmission power of the route request packets; as before, unicast packets use the RBAR mechanism to automatically select an optimal transmission rate for a specific link. We developed two variants of the AODV protocol using "local" routing. In the "stateless" mechanism, nodes forwarding a broadcast packet simply use the same transmission state (range or power) used by the original node; this resulted in overall poor performance. In the "stateful" mechanism, each node remembers what transmission range or power was needed for successful transmission. Both the methods can selectively use transmission rate or transmission power as means to achieve "local" routing. The ns-2 network simulator was used as the test bed for our modifications to AODV.

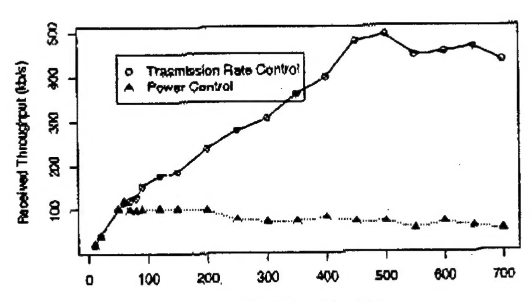
The results of our trials are compared to the default AODV settings which use maximum transmission rate and power. We found that reducing the transmission range, using either mechanism, without adaptation partitions the network. Figure 7(a) compares the goodput achieved with the "stateless" and "stateful" algorithms against the default AODV performance. The figure shows the end-to-end goodput achieved with different node mobilities. The "stateless" scheme has uniformly poorer behavior. On further inspection of the simulation traces, it was observed that re-initiating route discovery at the lowest transmission range causes needless route requests to be sent. The problem becomes quite dominant in pathological cases where the next hop can only be reached at the highest transmission range. Consequently, our "stateful" algorithm introduced the notion of soft-state such that every node remembers the transmission rate of the last successful packet. Hence, one can re-initiate the route discovery at a more appropriate range. Using transmission power control to route "locally" instead of transmission rate gives slightly better performance because reducing power limits the carrier sense range as well as limits the number of nodes that can respond to a route request. Figure 7(b) summarizes the corresponding effect on the latency. Using the stateful algorithms increases the latency compared to the baseline AODV implementation be-



(a)



(b)



(c)

Figure 7: Figure (a) compares the "stateful" and "stateless" algorithms using both transmission power control and transmission rate with the default AODV. The "stateless" algorithm leads to degradation in throughput. The "stateful" algorithm performs significantly better. Figure (b) shows the corresponding effect on the latency. Figure (c) shows the how overall throughput is affected by the two range control mechanisms.

cause the stateful algorithms must spend time adapting to traffic conditions. The increased latency is balanced by the increased goodput. Although the stateful mechanisms both spend time adapting, that extra time results in less routing overhead and improved goodput.

In our approach, we have used transmission power control and transmission rate independently. We saw that using transmission power control reduces the noise floor as it decreases the carrier sensing range. However, adapting transmission rate also has the additional benefit of using higher bandwidth links. This is illustrated in Figure 7(b), which shows the throughput achieved as the message injection rate is increased. The transmission range for this experiment was set at that of an 11Mbs link. Thus, we see that by using transmission rate control we can achieve higher throughput by using higher capacity links.

We believe that this simple experimentation shows the promise of using our abstraction. The notion of "broadcasting locally" improves performance for an existing routing protocol. More importantly when the lower layers in the protocol stack are free to choose one range control mechanism over another, the overall throughput of the network can be improved without encoding knowledge of the lower layers in our command and configuration interfaces.

4 Related Work

The properties of wireless networks make porting of the traditional protocols such as Transmission Control Protocol (TCP) difficult. While TCP is carefully calibrated to overcome the problems of stability and congestion control, wireless architectures introduce new challenges such as network partition and link failure due to mobility as well as different error characteristics. For example, traditional TCP error control is centered on congestion losses and ignores the possibility of transient random errors or temporary "blackouts" due to hand-offs and extended burst errors that are typical in wireless networks. As a result, different cross-layer approaches were introduced to overcome the deficiency of traditional TCP. A good summary of such techniques is given in [23, 24]. Balakrishnan [25] and Bakshi [26] explored different approaches including many cross-layer approaches involving the link layer. One such approach was the use of a *snoop agent* that monitors the traffic at the base station and caches the TCP segments. It retransmits the lost packet from its cache. This could be viewed as one implementation of a "*transmit reliably*" adverb, and could be combined with transmit power and modulation control.

All of these mechanisms, and more, can be classified and used to implement the more abstract notions of "adverbs" or modifiers on actions. The challange will be to have the different mechanisms be used at the appropriate time and at the correct level in the communication hierarchy.

5 Discussion

Our experiments have shown that control of transmission range (the *locally* adverb) may be achieved by either controlling transmission rate or power, but that these mechanisms have different effects. While the impact on goodput and latency is similar, the effect on *aggregate* throughput is markedly different. Utilizing higher transmission rates results in more efficient use of the spectrum and increased aggregate bandwidth. The experiments also showed that being able to route *locally* by either mechanism reduces in the number of routing messages generated, also improving the efficiency of the network.

From the perspective of the routing layer, sending a packet *locally* has the simple goal of reducing the number of control messages produced by limiting their scope of distribution. Since either mechanism achieves these goals, it is not productive for the routing layer to choose one over the other. We have shown that the routing protocol is better served by using an abstract interface specification, such as *locally*, which defers the decision to a lower layer that has more detailed knowledge of the hardware involved, its capabilities, and current network channel conditions. Such an approach was also suggested by Choudhury [2], specifically relying on the link layer to decide between two equally good routes. In our case, the choice of mechanism could depend on factors such as average message sizes in a flow. Message flows with large packets would use transmission rate control since that results in a higher bandwidth route. Flows will small messages could use transmit power control.

More importantly, as new RF interfaces become available the intent of *locally* will not change, although the physical mechanism to implement it may. Some hardware may be capable of large variations in data rate encoding but have very few power control levels, or vice versa. Tightly coupling the routing layer to such capabilities needlessly limits its ability to adapt to diverse hardware.

6 Conclusion

This paper is a first step toward defining a set of adverbs and adjectives suitable for flexible and intelligent utilization of available network resources. We have shown how it may be applied to *ad hoc* wireless network algorithms. Our survey of prior work indicates that most current cross-layer optimizations use limited information about the link layer and affect few physical mechanisms to control the RF layer. This implies that a careful "meta-protocol" design should be able to define a framework that would provide sufficient information for these cross-layer algorithms. We are currently working on implementing such a framework on a networking research testbed, paying particular attention to the mechanisms made available by software radio.

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